

Interactivity of language

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Abstract

In previous decades, the language sciences made important advances by dividing language into its different information formats, such as phonetics, semantics, and syntax. Such division generally implied that language processing is divorced from context. In more recent decades, however, important advances in the language sciences have been made in understanding how linguistic information interacts with context. These contextual influences stem from a broad range of sources. They include linguistic and non-linguistic processes within and between individuals. This brief review touches on experimental results from both behavioral and neural measures, and from both individuals processing prepared linguistic stimuli and dyads sharing unscripted conversation. Overall, the findings generally support a view of language processing that must somehow allow for the different information formats of language to retain their unique labels but also accommodate the fact that they frequently interact and overlap with other, even non-linguistic, formats of information.

1 | INTRODUCTION

When a science is new, its practitioners often assume that they can “carve nature at its joints,” and thereby identify the elements that get added together to produce the phenomena that are studied by that science. However, as a science matures, its practitioners gradually learn that when those elements interact to generate the phenomena, they are not as separable as initially assumed, and their combination is not at all additive but in fact quite nonlinear. Over several decades, this has happened in physics, in chemistry, and in biology (Capra & Luisi, 2014;

Laughlin, 2005). It is now happening in the cognitive and social sciences. We focus here on the way that these nonlinear interactions (or context effects) have been discovered in real-time language processing.

This brief review examines the field as roughly forming a 2×2 factorial design that makes four classes of methods. Different language laboratories tend to either emphasize behavioral measures or neural measures, and they tend to either study how an individual processes scripted language input or how a dyad of two people share unscripted conversation. As we review these four different approaches below, a constant mantra appears to dominate. Whether it is multiple linguistic information formats that are in question, or multiple brain regions being recorded, or multiple people that are involved, the data systematically reveal a fluid back-and-forth flow of nonlinear interactions that is robust and inescapable. Language processing is highly interactive.

2 | BEHAVIORAL MEASURES OF INTERACTIVE LANGUAGE PROCESSING IN A HUMAN

Over the past few decades, research using online behavioral measures such as priming, self-paced reading, and eye-tracking has helped paint a picture of a language processing system that is highly interactive, continuously incorporating input from a variety of contextual sources (cf. Knoeferle & Guerra, 2016; Marslen-Wilson, 1987; McRae & Matsuki, 2009; Onnis & Spivey, 2012). The utility of these methods derives from the temporal nature of language: As language unfolds, it is filled with temporary phonetic, lexical, syntactic, and semantic ambiguities. As humans resolve these ambiguities, online behavioral measures allow for tracking the influence of a given contextual source of information in real time.

Starting at the timescale of hundreds of milliseconds, research on the resolution of phonetic ambiguities has shown that, although speech sounds generally get categorized into one or another phonemic representation (Liberman, Harris, Hoffman, & Griffith, 1957), it takes at least a few hundred milliseconds for this perceptual categorization to be gradually completed (McMurray, Tanenhaus, Aslin, & Spivey, 2003; Pisoni & Tash, 1974). It is during these few hundred milliseconds of uncertainty that reaction-time experiments have shown that context from phonetic, semantic, and syntactic information formats can influence how the ambiguous speech sound gets categorized (Connine, 1987; Ganong, 1980; Holt & Lotto, 2002). In fact, even visual information (of mouth shape during speech, for example) can influence phoneme recognition (McGurk & MacDonald, 1976). Moreover, co-articulation effects between adjacent phonemes that span two words appear to be compensated for by lexical information from the first word feeding back to phonetic processes during the onset of the second word (Elman & McClelland, 1988; Magnuson, McMurray, Tanenhaus, & Aslin, 2003; McClelland, Mirman, & Holt, 2006; Samuel & Pitt, 2003). Toscano and McMurray (2010) showed that a neural-network-inspired model that statistically combines acoustic cues accurately simulates phoneme categorization effects and their development during language acquisition.

Moving up to the timescale of a second, research on the resolution of lexical ambiguities has often made use of cross-modal priming or naming tasks to demonstrate the influence of semantic context. In these tasks, subjects are presented with a semantically ambiguous stimulus (e.g., “Bug” can mean “insect” or “spy”) in one modality, such as auditorily over headphones, and then they are prompted with one of the possible resolutions of the ambiguity in another modality, such as visually written on a computer screen. Reaction times to respond to the prompts are

taken as a measure of the relative activation of the possible meanings. Using this method, it was found that multiple meanings of an ambiguous word were primed simultaneously for a brief period of time, even when previous context biased one or the other interpretation (Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982; Swinney, 1979; Tanenhaus, Leiman, & Seidenberg, 1979; see also Tanenhaus & Lucas, 1987). This early work supported the claim that lexical access first occurs in an independent stage of processing, with semantic context playing a role only in a later lexical selection phase. However, subsequent research has contradicted these initial conclusions, revealing immediate influence of semantic context under certain circumstances. For example, highly constraining contexts that more strongly bias one particular meaning (especially the statistically dominant meaning) can profoundly influence even the initial moments of lexical access (Simpson & Krueger, 1991; Tabossi, 1988; Vu, Kellas, & Paul, 1998; see also Huettig & Altmann, 2004). And neural network simulations have provided insight into how contextual biases may always be influencing lexical ambiguity resolution, just in a sufficiently gradual fashion that it may not appear in some behavioral measures for a few hundred milliseconds (Kawamoto, 1993; see also Van Orden, Guy, Pennington, & Stone, 1990).

As we move further up to the timescale of several seconds, we see that syntactic processing has also shown sensitivity to context. Trueswell, Tanenhaus, and Garnsey (1994) found that the tendency to incorrectly parse a sentence (the garden path effect) was modulated by whether or not the first noun encountered was animate or inanimate, and thus likely or unlikely to be an agent of the action denoted by the verb. McRae, Spivey-Knowlton, and Tanenhaus (1998) showed that this effect can also be produced by varying thematic fit, such as whether or not a given noun is likely to perform the particular action, while holding animacy constant.

Statistical regularities in a language also appear to influence syntactic processing. In three experiments using cross-modal naming, self-paced reading, and eye-tracking during reading, Trueswell, Tanenhaus, and Kello (1993) found that a garden path effect with a sentence complement emerged more strongly after verbs that are frequently used with a noun complement than after verbs that are frequently used with a sentence complement, showing that syntactic processing is immediately sensitive to statistical regularities in the lexicon (see also, MacDonald, Pearlmutter, & Seidenberg, 1994). Phonological properties of word categories also carry statistical regularities. Farmer, Christiansen, and Monaghan (2006) used naming latencies and self-paced reading to show that the phonological typicality of nouns and verbs, relative to their respective categories, affected syntactic processing. That is, a noun whose phonology was statistically similar to that of a verb tended to affect syntactic processing as though it was partially a verb; and vice versa for verbs with phonology similar to that of a noun.

Discourse context is another rich source of contextual information available during language processing. Using self-paced reading and eye-tracking during reading as measures of processing difficulty for syntactically ambiguous phrases, it was found that a referential ambiguity introduced in the discourse can bias participants' syntactic preferences, thereby preventing a garden-path effect (Altmann & Steedman, 1988; Spivey & Tanenhaus, 1998). Other studies using behavioral methods to investigate the interpretation of ambiguous pronouns have shown that listeners rapidly integrate a variety of other cues from the discourse context, including gender, order-of-mention, and salience (Arnold, Eisenband, Brown-Schmidt, & Trueswell, 2000; Kaiser & Trueswell, 2008).

Non-linguistic factors such as visual context can also influence language processing. For example, eye-tracking and computer-mouse tracking methods have revealed continuous integration of visual and phonological information during spoken word recognition (Alloppenna, Magnuson, & Tanenhaus, 1998; Spivey, Grosjean, & Knoblich, 2005). These two methods have

been used to show that syntactic processing can be biased by visual information, such as how many referent objects are present in a scene. For example, the sentence “Put the apple on the towel in the box” describes a situation in which “on the towel” is the original location of the apple. However, because the sentence is temporarily ambiguous, participants often look at the apple and then an irrelevant blank towel, indicating that they initially interpreted “on the towel” as a destination (i.e., the goal of the verb phrase). But when the visual context contains two apples, participants immediately interpret “on the towel” as a noun-phrase modifier and look at the apple that’s on a towel and then the box, rarely looking at the irrelevant blank towel (Spivey, Tanenhaus, Eberhard, & Sedivy, 2002; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995; see also Farmer, Cargill, Hindy, Dale, & Spivey, 2007). For related eye-tracking examples of visual context immediately influencing real-time sentence comprehension, see Altmann and Kamide (2007), Knoeferle and Crocker (2006), and Anderson, Chiu, Huette, and Spivey (2011).

Finally, language processing has also shown to be “embodied,” in that there are demonstrable interactions with systems involved in perception, action, and emotion (for a review, see Barsalou, 2008). Behavioral research on these “embodied” effects has often made use of priming and reaction time measures. For example, Glenberg and Kaschak (2002) found that responses to action sentences (e.g., “close the drawer”) were faster when the participant’s response movement was consistent with the implied direction of the action (extending the hand away from the body to reach the response button). Zwaan, Stanfield, and Yaxley (2002) used priming to show that participants form representations of objects’ visuospatial properties while reading. Richardson, Spivey, Barsalou, and McRae (2003) extended these findings to show that memory for object pairs was improved when their spatial orientation matched the orientation suggested by the image schema of the verb used to refer to them. Related work by Vigliocco, Vinson, Lewis, and Garrett (2004) used naming tasks to provide evidence that memory for words is stored in modality-specific representations of features (see also, Yee, Huffstetler, & Thompson-Schill, 2011). Thus, not only are linguistic and perceptual information sources acting as context for language processing but so are the body’s own sensorimotor constraints.

3 | NEURAL MEASURES OF INTERACTIVE LANGUAGE PROCESSING IN A HUMAN

The pattern of findings supporting interactivity in language that is observed in the behavioral literature also shows up when language is studied with neural measures. A variety of neural measures, such as electroencephalography (EEG), magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI), and transcranial magnetic stimulation (TMS) studies have all been incredibly useful in identifying when and how different cortical networks related to language processing interact with one another. Just as behavioral measures had suggested that it takes a few hundred milliseconds for phoneme categorization to be gradually completed, event-related potentials recorded from EEG signals show the same result (Toscano, McMurray, Dennhardt, & Luck, 2010). During these few hundred milliseconds, cortical networks that are specialized for semantic processing rapidly influence cortical networks that are specialized for phonetic processing. For example, Gow and Olson (2016) recorded MEG signals from participants while they listened to speech-synthesized words with an onset phoneme that was ambiguous between /t/ and /d/, resulting in perception of the

word as either “tusk” or “dusk.” When preceded by a phrase like “The moon rises at ...,” people routinely heard that phonetically ambiguous word as “dusk.” To look at the interaction between brain areas related to lexical and phonetic processing, Gow and Olson examined the timing of activity patterns in multiple cortical areas. If two areas are correlated, then small temporal differences in the timing of these activity patterns may be used to infer the direction with which certain areas are influencing others. They found that the posterior portion of the left medial temporal gyrus (pMTG) and the left supramarginal gyrus (SMG), cortical regions associated with lexical processing, were both reliably influencing the activity of the posterior portion of the superior temporal gyrus (pSTG), a cortical region associated with phonetic processing (see Spivey, 2016 for discussion). Moreover, fMRI measures of audiovisual speech perception have shown that the left superior temporal sulcus (STS) may function as a kind of “convergence zone” (Damasio, 1989) where visual information about mouth shape during speech can influence phoneme perception (Calvert, Campbell, & Brammer, 2000).

Neuroimaging studies have also revealed that the left hemisphere plays a particular role in selecting linguistic forms given a particular context. EEG results suggest that the left hemisphere is better than the right hemisphere at both *maintaining* activation of two meanings of a semantically ambiguous word and at rapidly integrating context for *selecting* only the appropriate meaning (Meyer & Federmeier, 2007). Results from fMRI experiments show that unambiguous sentences that contain several ambiguous words elicit increased activation in the posterior portion of left inferior temporal cortex, and also in both the left and right inferior frontal gyri (Rodd, Davis, & Johnsrude, 2005). Results like these fit with the claim that the left inferior frontal cortex deals particularly with selecting among competing alternatives, especially during language processing (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997).

We are able to illustrate how such selection processes occur by turning to neural network simulations. For example, Kawamoto (1993) simulated word recognition in a neural network that is fully connected between nodes representing orthographic, phonetic, and semantic features. The connections are trained by presenting the network simultaneously with orthographic, phonetic, and semantic features from a set of lexical items. As with behavioral and neuroimaging evidence, the model demonstrates that automatic bottom-up word recognition processes immediately interact with top-down contextual processes to influence the activation of lexical representations (see also Lee & Federmeier, 2009). As such, top-down contextual processes can never instantaneously and summarily prevent the activation of contextually disfavored lexical representations. But they can quickly ramp down the activation profile of one. Thus, we may view word recognition as the result of competition and cooperation between these top-down and bottom-up processes. Hence, context is always involved in word recognition, even in cases where the contextually disfavored lexical representation is selected.

Similar findings have been reported for understanding how context affects syntactic processing. EEG studies have shown that when a referential ambiguity introduced by context prevents a syntactic garden-path effect, the influence is not delayed by the transition time from one stage of processing to a second stage of processing; it is immediate (van Berkum, Jos, Brown, & Hagoort, 1999). Related work has shown that a highly constraining discourse context can make an anomalous sentence get processed as though it has no anomalies (Nieuwland & van Berkum, 2006) and can even elicit the anticipation of specific upcoming words (van Berkum et al., 2005). More recent EEG studies have begun to explore exactly how it is that different brain regions might cooperate with each other to carry out these context effects, finding that phase synchronization of large-scale neuronal activation patterns may be fundamental (e.g., Lam, Bastiaansen,

Dijkstra, & Rueschemeyer, 2017; Lewis, Schoffelen, Hoffmann, Bastiaansen, & Schriefers, 2017; Rommers, Dickson, Norton, Wlotko, & Federmeier, 2017; see also Falandays, Batzloff, Spevack, & Spivey, in press).

Finally, just as has been observed with the behavioral measures discussed in the previous section, neural measures of language processing have revealed that language is “embodied.” Language is not processed solely by a brain that has no grounding in its sensorimotor interface with the world. The world-based information that linguistic cortical networks use to build a situation model of the discourse is not merely abstract symbolic representations of the world; it is the analog sensory and motor information gathered from how the body actually interacts with the world. The cortical networks that process perception and action interact with the cortical networks that process language. For example, fMRI studies show that reading sentences about actions that involve the face, arm, or leg elicits activation in motor cortex regions associated with the tongue, fingers, or feet, respectively (Hauk, Johnsrude, & Pulvermüller, 2004). These researchers then used TMS to show that this activation was not just an epiphenomenal spreading of activation, but it actually plays a functional role in real-time language processing, such as in a lexical decision task (Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005). Moreover, TMS studies have shown that tongue-related motor cortical areas are active during passive recognition of speech (Fadiga, Craighero, Buccino, & Rizzolatti, 2002), and during audiovisual speech perception (Sato, Buccino, Gentilucci, & Cattaneo, 2010). Part of understanding speech involves the partial activation of the motor areas that would be involved in producing that speech (Galantucci, Fowler, & Turvey, 2006). In fact, the participants who show better performance in recognizing speech amid noise are exactly the ones with stronger activity in those tongue-related motor cortex areas (D'Ausilio et al., 2014). Similar findings are observed for reading and writing as well. Hand-related motor cortical areas are active during passive visual recognition of gradually presented handwritten letter sequences (Gordon, Spivey, & Balasubramaniam, 2017).

Clearly, the behavioral and neural evidence overwhelmingly supports rapid interaction and overlap among the cortical networks that appear specialized for different formats of information in language, perception, and action. This overlap in neural computation may compromise somewhat the tradition of referring to these cortical networks as “a phonology module” or even “a language module.” For example, if the function of a cortical network that is known to process linguistic information is immediately taking into account contextual influences from a cortical network that is known to process motor movement information, then it seems clear that this “linguistic cortical network” is processing more than just linguistic information.

4 | BEHAVIORAL MEASURES OF INTERACTIVE LANGUAGE PROCESSING AMONG HUMANS

While the majority of experimental language research has been conducted with one person at a time processing carefully controlled linguistic stimuli, the more ecologically valid situations of language use tend to involve two or more people sharing an unscripted conversation. In the past, linguistic analyses of realistic conversations have hinted at the interaction between lexical, semantic, syntactic, and pragmatic processes (Clark, 1992), but only recently have real-time laboratory measures been able to densely sample the behavioral coordination that takes place across those different formats of linguistic representation during natural conversation. Not only

do different cortical regions engage in various forms of synchronization to carry out their coordination (Hauk, Giraud, & Clarke, 2017) but so do different body parts, and different people.

Recent work on language synchronization between individuals has drawn heavily from preceding studies of motor synchronization and mimicry between people and studies on nonverbal signaling. These studies show how two subsystems (e.g., two limbs or two people) can be described in dynamical systems terms as becoming one cognitive system (Spivey, 2013; see also Gallotti & Frith, 2013). For example, when moving opposite fingers or limbs from slower to faster rates, a phase transition takes place where intended anti-phase movements accidentally transition into in-phase movements. This was famously demonstrated by Kelso (1984) when he showed that people alternately lifting their right and left index fingers in such a way that one is flexed upward while the other is flexed downward (anti-phase) will result in both fingers rising and falling in synchrony as the speed of the movements is increased. The same occurs between people. Two people swinging their legs in anti-phase will unintentionally synchronize their movements so that the swinging of their legs is matched (Schmidt, Carello, & Turvey, 1990). More than a mere parlor trick, this kind of motor synchronization actually results in increased positive affinity between two people (Hove & Risen, 2009).

Similar kinds of motor synchronies naturally emerge during linguistic interaction as well. Even when two people aren't trying to coordinate their motor movements, simply talking back and forth about a shared puzzle, the ordinary miniscule movements of their center-of-mass (i.e., postural sway) adventitiously become correlated (Shockley, Santana, & Fowler, 2003). Postural sway coordination increases when dialogue speed increases, or when speakers say the same words, or words with similar stress patterns (Shockley, Baker, Richardson, & Fowler, 2007). And when people have reason to be less cognitively connected, such as differing social groups (Miles, Griffiths, Richardson, & Neil Macrae, 2010), or when they are engaged in a debate (Paxton & Dale, 2013), this motor coordination is disrupted. When one participant is intentionally deceiving another, the deceiver begins exhibiting dynamically unstable movements of facial muscles, which breaks down the motor coordination (Duran, Dale, Kello, Street, & Richardson, 2013). At multiple timescales, humans tend to mimic the postures, word choices, facial movements, speech acts, head movements, grammatical patterns, and even laughter of people around them (Chartrand & Bargh, 1999; Lakin, Jefferis, Cheng, & Chartrand, 2003; Louwerse, Dale, Bard, & Jeuniaux, 2012; Pickering & Garrod, 2004). Such mimicry results in coordination of two or more human bodies in ways that both convey and parameterize meaning.

Coordination of pointing and posture can be used as communication signals in a joint task (Athreya, Riley, & Davis, 2014). This type of signaling can take the form of pointing to locations and objects or simply placing objects, or oneself, in a location as a referent for the addressee (Clark, 2005). In groups, this type of nonverbal signaling is a very important part of communication and aids in mutual understanding and coordination toward completing a shared task (Clark & Krych, 2004).

There is also work examining eye movements in order to show how two individuals coordinate during linguistic communication. Ambiguity in meaning can be quickly resolved using gaze. Hanna and Brennan (2007) showed that when visual displays are very similar, rather than waiting for a verbal description of the differences, addressees will naturally utilize gaze information from the speaker to determine which display is being referred to. Additionally, a tighter coupling between the gazes of a person describing a scene and a person listening to the description—meaning that the listener looks at the same parts of the display as the speaker does, with only about a one-second delay—results in improved communication of information (Richardson & Dale, 2005). And when the language transfer about that shared image is a two-way

dialogue that the dyad co-creates together, gaze coupling no longer even shows that one-second delay. Participants are naturally looking at the same parts of the display at exactly the same time (Richardson, Dale, & Kirkham, 2007). Moreover, when participants who are engaged in a dialogue believe their partner is seeing the same scene as they are, gaze coupling is increased as compared to when they believe that their partner does not see anything (Richardson, Dale, & Tomlinson, 2009).

In spoken language, mimicry and synchronization are exhibited in phonetic convergence, also known as speech alignment. Speech alignment is the tendency of one person to use the same rhythm, stress, intonation, and pitch as another speaker. It occurs not only when people shadow the words they hear (Miller, Sanchez, & Rosenblum, 2013; Shockley, Sabadini, & Fowler, 2004) but also the words they shadow by lipreading (Miller, Sanchez, & Rosenblum, 2010), and paying attention to specific articulatory movements (Dias & Rosenblum, 2016). Visual recognition of speech increases speech alignment. Speech alignment is so integral that it even takes place when shadowing speakers with speech disabilities (Borrie & Liss, 2014).

There are also extralinguistic speech cues in conversation that are intended to convey information. Such cues can be as simple as using “uh,” “um,” “wow,” etc. in conversation. This type of backchannel may be used in conversation to signal that the speaker will be continuing to speak after the pause (Clark & Tree, 2002). Backchannels can have very general or very specific meanings and may frame a statement (Tolins & Tree, 2014).

In addition to coordination via pragmatic cues, syntactic patterns also show coordination between adults (Pickering & Ferreira, 2008), as well as between children and adults (Dale & Spivey, 2006). These various coordinative structures in language use develop through task sharing (Fusaroli et al., 2012), while content is altered based on social relevance (Galati & Brennan, 2010). Essentially, the behavioral data show that, as two people co-create a shared dialogue, information patterns at multiple levels of representation are passed back and forth so fluidly that the two people cannot help but become substantially correlated with each other in their speech acts, grammatical patterns, word choices, and motor movements of many kinds (Fusaroli & Tylén, 2016; Pickering & Garrod, 2004; Spivey & Huettenlocher, 2016).

5 | NEURAL MEASURES OF INTERACTIVE LANGUAGE PROCESSING AMONG HUMANS

In the above section, we discussed the behavioral entrainment of interlocutors as they linguistically communicate. If body movements are becoming correlated, it stands to reason that the brains driving those body movements may be correlated as well. According to the interactive-alignment model (Menenti, Pickering, & Garrod, 2012; Pickering & Garrod, 2004), interlocutors share a desire to mutually understand the state of affairs (or situation model) described by the current linguistic discourse. Brain-to-brain entrainment at each linguistic level enables interlocutors to converge on the same situation model. We have already discussed the within-brain connectivities that support such interactive dynamics within individuals. Here, we review evidence that individual brains are part of a larger dynamic interactive process, particularly when the people that own them interact with each other linguistically.

Studies looking at brain coupling across individuals have only emerged relatively recently with the development of statistical techniques to look at inter-brain correlations. Many of these studies use a methodology known as hyperscanning. This methodology refers to any experiment in which the neural activity patterns of two (or more) individuals are simultaneously recorded

as these individuals interact (e.g., while talking; Montague et al., 2002). In some cases, hyperscanning is approximated by sequentially recording two participants, with the second participant listening to the audio-recorded speech of the first participant. Such studies only show how the listener's brain entrains to the speaker's, and not the reverse. Hyperscanning and pseudo-hyperscanning methods have been successfully used in many social interaction studies (see Konvalinka & Roepstorff, 2012 for review). However, as the use of hyperscanning in language interaction studies is somewhat limited, we include relevant single-brain and pseudo-interactive studies in this section as well.

Earlier studies focused on measuring the brain activations of individuals engaged in either speaking or listening, without a partner. If language processing is part of an interactive process between speakers and listeners, then it is reasonable to suggest that there are similarities between individuals engaged exclusively in speaking and those engaged in listening. Indeed, these earlier single-brain investigations of language perception and production found similar brain activities during perception and production of speech (Fadiga et al., 2002), lexical items (Ilmberger, Eisner, Schmid, & Reulen, 2001), and syntax (Segaert, Menenti, Weber, Petersson, & Hagoort, 2011). It is possible that brain areas that are roughly specialized for speaking and listening are simultaneously engaged, even in exclusively speaking or listening contexts, because language is naturally an interactive process in which speaking and listening occur simultaneously. A speaker utilizes speech perception areas to better understand their own utterances as heard by the listener and vice versa. If this is true, then one should expect to see correlations between these cortical regions when examining the brains of two individuals engaged in naturalistic interactive conversation.

In a pseudo-hyperscanning study, brain activation patterns from speakers and listeners were recorded by Stephens, Silbert, and Hasson (2010) using fMRI. Participants gave unrehearsed real-life narratives, which were then presented to a second set of participants. Speaker and listener brain activation overlapped in several wide-spread regions. The strength of brain coupling correlated with the degree to which the listener comprehended the narrative of the speaker. In the absence of any understanding, when speaker narratives were in a language that the listeners did not understand, no correlations were found. This result indicates that coupling arises from language exchange, rather than simply from a shared audio signal. Kuhlén, Allefeld, and Haynes (2012) used a similar pseudo-hyperscanning method with speakers and listeners having their EEG activity recorded. A male speaker and a female speaker were recorded visually and auditorily, and their video and audio tracks were overlaid as one movie. Participants who were instructed to attend only to the female speaker and her narrative exhibited EEG patterns that correlated substantially with female speaker's EEG pattern, and less so with the male speaker's EEG pattern. The inverse pattern was observed for the participants instructed to attend to the male speaker. This brain-to-brain entrainment between speaker and listener showed peaks at multiple time scales (see also Spiegelhalder et al., 2014).

While these results support the notion that linguistic brain coupling arises from the process of mutual understanding, one could in principle argue that the brain-to-brain coupling may be driven simply by the fact that the auditory systems of the listener and speaker are attending to the same auditory stimuli (i.e., the speaker's speech). Pérez, Carreiras, and Duñabeitia (2017) ruled out this alternative explanation by further examining this brain-to-brain coupling with interacting dyads who took turns exchanging verbal narratives, in the absence of visual contact. First, correlations for brain activity between speakers were calculated. Next, as a control measure, separate correlations were calculated between the brain activations of each individual and the amplitude of the spoken conversations. Significant correlations were of course found

between the amplitude envelopes and the speaker EEG activations, as well as between the amplitude envelopes and the listener EEG activations. Entrainment to the amplitude envelopes of the auditory speech stream significantly explained much of the correlations between speaker and listener EEG signals. However, after accounting for this mediation, brain-to-brain coupling was still observed over and above those purely auditory-driven correlations.

Further evidence shows that brain-to-brain coupling is predictive in nature. Dikker, Silbert, Hasson, and Zevin (2014) used fMRI and speakers to describe a set of cartoon images, constructed to elicit highly consistent sentences for that image (e.g., “the penguin is hugging a star”) or rather inconsistent sentences (e.g., “the guitar is boiling a wheel,” or “the guitar is cooking the tire,” or “the guitar is stirring the bike”). When listeners saw those images, scenes that had highly predictable descriptions elicited greater activity in the left posterior superior temporal gyrus (pSTG) than did the less-predictable scenes (possibly indicating some anticipation of likely descriptions). When they then heard the speaker’s recorded description of the scene, pSTG activity over time in the listener was reliably correlated with pSTG activity over time in the speaker—but only for highly predictable scenes. Dikker et al. interpret these results as evidence that a listener’s ability to predict a speaker’s utterance magnifies the brain-to-brain entrainment between speaker and listener.

Neural measures of naturalistic conversation suggest that brain-to-brain entrainment does not merely arise out of synchronization to a shared linguistic signal. Rather, the neural entrainment of interlocutors arises out of a mutual desire to understand the meaning of the communicated signal. Roepstorff and Frith (2004) suggest that top-down modulation within an individual brain is something that must emerge from brain-to-brain coupling, much like that seen in the broader social interaction literature. Overall, these studies highlight the claim that language is in its essence interactive and that it is crucial to utilize interacting participants to study the neural underpinnings of language in an ecologically valid manner.

6 | CONCLUSION

The historical progression of research on interactions in language processing provides a relatively clear lesson: Whenever evidence was produced that suggested some aspect of context was briefly ineffective, follow-up studies revealed that more strongly constraining versions of those contexts were immediately effective. Rather than treating the lack of a context effect as evidence for limitations on the cognitive architecture of the language processing system, the constellation of results is now interpreted as evidence for a graded probabilistic integration of many conflicting biases all at once during real-time language processing. Sometimes a context has a weak influence simply because all the bottom-up input happens to strongly bias the contextually inappropriate interpretation at that moment (Tanenhaus, Spivey-Knowlton, & Hanna, 2000). There are still some arguments that remain in the literature in favor of modular non-interactive accounts of language processing (Norris, McQueen, & Cutler, 2000; Rayner & Reichle, 2010; Staub, 2011). However, the abundance of evidence appears to outweigh those claims (Kamide, 2008; Knoeferle & Guerra, 2016; McRae & Matsuki, 2009; Spivey, Joanisse, & McRae, 2012). Particularly when two people co-create an unscripted natural conversation, the same kind of continuous back-and-forth flow of information that is seen between syntactic information and semantic information (Tanenhaus & Trueswell, 1995), and between language cortices and sensorimotor cortices (Hauk et al., 2004), is also seen between two people (e.g., Dale, Fusaroli, Duran, & Richardson, 2013; Schoot, Hagoort, & Segaert, 2016).

Based on our overall assessment of findings here that support interactivity, it seems clear that when humans and their brains are processing language with each other, there is no format of linguistic information (e.g., lexical, syntactic, semantic, and pragmatic) that cannot be rapidly influenced by context. By the same token, there is also no brain region or human body that cannot be rapidly influenced by context during natural language processing. When those context effects appear delayed, it is more likely due to the natural temporal dynamics of competition and cooperation between the various information sources, not due to architectural constraints on the language processing system that summarily preclude them from being instantaneous. Moreover, interaction—whether between the traditional linguistic formats, language, and other aspects of cognition with an individual or between multiple individuals—can be seen as the process through which context affects linguistic processes. This interactivity is continuous in time and nonlinear in its effects. Thus, even in cases where context appears to have had a relatively small effect on the linguistic forms that are perceived or spoken, context is consistently part of language processing.

It is important to note, nonetheless, that once a nonlinear interactive account of language processing is accepted in the field, the hard work has only just begun. The task for the field at this point is to develop a theoretical apparatus that can account for these interactions in language processing in a manner that is clear, explicit, and makes quantifiable predictions. That theoretical apparatus might be a rule-and-symbol system that quickly integrates contextual influences (Budiou & Anderson, 2004; Jurafsky, 1996), or a complex and adaptive continuous dynamical system (Beckner et al., 2009; Elman, 2009; Onnis & Spivey, 2012), or some combination of the two (Dale & Spivey, 2005; Smolensky, Goldrick, & Mathis, 2014). Only the future holds the answer.

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How to cite this article: Spevack SC, Falandays JB, Batzloff B, Spivey MJ. Interactivity of language. *Lang Linguist Compass*. 2018;e12282. <https://doi.org/10.1111/lnc3.12282>